Stabilized frequency transfer for the Square Kilometre Array

D. GOZZARD [1] & S. SCHEDIWY

School of Physics, The University of Western Australia
[1] Corresponding author ✉ david.gozzard@research.uwa.edu.au

The Square Kilometre Array (SKA), due to begin construction in 2018, will be the largest radio-telescope ever constructed, and will incorporate clusters of antennas placed up to 150 km from the core site. Phase-coherent frequency reference signals must be distributed to each antenna in the SKA network in order for the array to function properly. The conventional method for a telescope of this extent would be to install individual atomic clocks (particularly hydrogen-masers), housed in temperature-controlled, vibration-isolated rooms, at each antenna cluster. This is extremely expensive to both construct and maintain and the SKA Office intends to employ stabilized signal dissemination systems as a much more cost-effective way of delivering coherent references signals to each antenna over such large distances.

The stabilized transfer system developed in the School of Physics at the University of Western Australia uses a continuous-wave laser that is modulated at the desired reference frequency and transmitted via fibre link to the receiver. A portion of the signal is reflected from the receiver unit back along the same fibre link to the transmitter, where it is compared to the original reference signal. The disturbances on the transmission line can then be measured and the out-going signal adjusted in order to account for these disturbances.

The modulation of the continuous-wave laser is achieved by splitting the optical signal from the laser into the two arms of a Mach-Zehnder Interferometer (MZI). Acousto-optic modulators (AOMs) in each arm of the MZI apply separate frequency shifts to the split optical signals. The shifted optical signals are recombined at the output of the MZI and are sent via fibre-optic cable to the receiver at the antenna. The difference in frequency between the two, shifted optical signals is the desired radio-frequency reference for use at the antenna. The two optical signals arriving at the antenna are frequency shifted again by an AOM in the receiver and a portion of their power is reflected back down the fibre link to the transmitter. The frequency shift at the receiver allows the transmitter to distinguish signals returning from the receiver from spurious reflections due to damage on the transmission line. The returning signals are beat against the original signal from the continuous-wave laser (that is, the returning signals are compared to the original laser signal) producing two radio-frequency beat signals that carry information about the frequency shifts caused by both the AOMs and the disturbances on the transmission line. Further electronic mixing of these beat signals reduces them to a form suitable to steer a PI controller, which applies a frequency modulation to one of the two transmitter AOMs calculated to pre-compensate the disturbances on the link.

A key feature of this system is that it uses optical detection (i.e. the optical heterodyne beat) to govern the modulation of a radio-frequency transmission. Most similar systems detect link disturbances in the radio- or microwave-frequency domain. Detection in the optical domain has advantages in sensitivity (due to the much shorter wavelength) and it is relatively easy to shield from spurious reflections from the fibre link using the frequency shift applied by the receiver AOM.

The SKA telescope is split between the African and Australian continents. Due to the geology of the South African SKA site, it is extremely expensive to bury the fibre transmission lines to the antennas and it would be much simpler and cheaper to the run the fibres along the over-head power lines also going to the antennas, but this makes the fibre lines extremely susceptible to disturbances caused by the wind. Using our optical-heterodyne detection system, we measured the signal instabilities on a 150 km link at the South African SKA site to be approximately 3500 times greater than on a buried 1840 km link in Germany measured by Droste and colleagues in 2013. Despite this unprecedented level of noise, our stabilization system was able to effectively suppress the instabilities on a 20 MHz transmission, even at wind speeds higher than the maximum operating requirement of the SKA telescope, and achieved a phase stability of 0.01 radians at an integration time of one second. Based on these results and previous laboratory tests of similar signal stabilization systems operating at other frequencies, it is likely that a similar level of stability will be achieved by systems designed to transmit the 350 MHz and 32 GHz reference frequencies required by SKA-low and SKA-mid. That is, these systems are expected to achieve a signal stability around 20 times lower than the SKA requirement of 0.2 radians at one second integration time. Thus the use of stabilized frequency dissemination technologies such as ours will enable the South African SKA site to use over-head transmission lines, saving the project millions of euros that it would cost to bury the fibre.

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